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Induction heating with the ring effect for injection molding plates ☆

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ABSTRACT

Induction heating in injection molding has the advantages of rapid heating, reduced cycle time, and improved product quality. In this research, using both experiment and simulation, externally wrapped coil induction heating was applied to verify the heating capacity of a pair of mold plates. By applying different coil designs and mold gap, the effect of the externally wrapped coil induction heating was evaluated. Results showed that when a serial coil was used as an inductor, the heating rate reached 8.0 °C/s. From an initial mold temperature of 40 °C, after 15 s heating, the mold surface temperature reached 159.9 °C with the serial coil. The parallel coil shows a better heating uniformity but its heating rate is far lower than the serial coil. For the serial coil, the temperature distribution between the core and cavity plate are almost the same. The heating rate increases from 4.9 °C/s to 10.6 °C/s when the inductor design is changed from 5 turns to 7 turns. After 15 s heating, the temperature at point T2 increases from 40 °C to 166.7 °C and 106.1 °C with a mold gap of 1 mm, and 6 mm, respectively.

1. Introduction

Injection molding technology has been widely used in almost all fields of plastic product manufacture. However, many problems may occur on molded parts, including warpage, shrinkage, surface quality issues and weld lines. To improve part quality, many solutions have been applied, including process parameter adjustment and material upgrades. Among them, dynamic mold temperature control is one of the most efficient methods for achieving part quality improvement [1,2]. At higher mold surface temperatures, the surface quality of the part will improve. However, cooling time increases as mold surface temperature rises, lengthening cycle times. A lower mold surface temperature reduces cooling time, but does not benefit part surface quality. Thus, a critical goal of mold heating is to increase the mold surface temperature while maintaining a reasonable cycle time.

For the mold heating process in injection molding, two main types of heating system are used, volume heating and surface heating. In recent research, with real molds, the steam heating shows a heating rate in the range of 1 °C/s to 3 °C/s [3]. This speed is quite slow and results in longer post-filling times. In another studies, the heating rate was increased by the method of surface heating. For processes that control the mold surface directly, a coating layer on the cavity surface has been shown to reduce the heat transfer from the melt to the mold material, increasing the temperature on the cavity surface by 25 °C [4,5]. Further, an infrared heating system has also been used for heating the mold surface. This system can heat the surface of one or two mold halves depending on the design [6,7]. In a recent application of surface heating, hot air was injected into a simple model of a mold cavity, the heating capacity of the gas and the quality of injection molded part were evaluated [8,9]. Hot gas can rapidly raise the mold surface temperature from 60 °C to 120 °C within 2 s, as a result, the product quality also can improve. However, the associated mold temperature reaches saturated values when the heating time exceeds 4 s. The advantage of gas heating is its high heating rate, which reduces cycle time. However, the mold must be appropriately designed if gas surface heating is used.

Similarly, an electromagnetic induction coil has been used to heat the cavity surface to reduce weld line, shrinkage, and other defects of the part surface, as well as to improve the part quality. In our recent investigation series [10–13], we have proposed the use of induction heating combined with low coolant temperature cooling for dynamic mold temperature control. Another type of induction heating uses the effect of high-frequency proximity to heat the cavity surface of the induction mold. Yao et al. [14] proposed using this effect for pre-heating the cavity surface of a micro injection mold with a cavity of 25 mm × 50 mm. With a properly designed mold structure, the heating effect can support for the micro injection molding by the pre-heating period. In the real application of industry, the wrapped coil [15,16] was added in to the mold structure to pre-heat the mold surface. This

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type of design shows a good performance in molding field. However, the design parameter of induction coil as well as the mold properties was not clearly studied.

In this study, an externally wrapped coil induction heating system with water cooling, under different coil designs (serial and parallel), number of turns (5 turns, 6 turns, and 7 turns), and mold gap (varied from 1 mm to 6 mm) was used to achieve rapid mold surface temperature control for a pair of mold plates. A set of systematic experiments was conducted to correlate the effect of heating conditions, including heating efficiency and temperature distribution uniformity. Using the ANSYS software, the heating process under different coil and mold designs was simulated and compared with experimental results. The feasibility of externally wrapped coil induction heating for mold surface temperature control during the injection process was evaluated.

2. Principle of externally wrapped coil induction heating in mold temperature control

The principle of externally wrapped coil induction heating is illustrated in Fig. 1. When the conductor, a rectangular bus bar, is bent to form a ring, then its current will be redistributed. The magnetic flux line will be concentrated inside the coil, and the density of the magnetic field will be higher inside the coil. As a result, most of the current will flow within the thin inside surface layer of the conductor. The wrapped coil effect will have a positive heating effect on the work piece located inside the induction coil because the combination of the skin and the proximity effects will lead to a concentration of the coil current on the inside diameter of the coil [17,18]. In the injection molding field, an injection mold consists of two mold inserts facing each other and forming a mold cavity in between. The mold inserts are typically made of high-strength tool steel, a material with high electrical resistivity. The injection mold with these properties is thus subjected to the induction heating effect when the magnetic field is applied. Because of the magnetic effect, an eddy current will appear at the surface of the core and cavity plate and generate electric heating on the surface. In a real mold structure, the channel beneath the plate provides a flow of water, so that the temperature of the mold can be heated to the initial temperature at the beginning and cooled after the heating process is finished. The penetration depth near the heating surface, δ *(m)*, may be described by

$$\delta = 503\sqrt{\left(\frac{\rho}{\mu f}\right)} \tag{1}$$

where f (cycle/s) is the alternating current frequency, ρ (Ω m) is the electrical resistivity, and μ is the relative permeability. The associated eddy current flow in an electrically resistant environment is finally dissipated as heat that causes the mold temperature rising.

3. Experiment and simulation work

The mold temperature control process using externally wrapped coil induction heating consists of an induction heating machine (IHTC-02) from INER Technology Co., LTD., a water mold temperature control system, a control and monitoring unit, a pair of stainless steel mold plates ($32\times100\times100$ mm^3), and an externally wrapped coil system. The induction heating machine supports a high-frequency current flow through the conductor and the mold plate with a full power of 50 kW. The inductor has two designs: a serial coil and a parallel coil. To cool the coil, a hollow channel is fashioned inside each coil. The coils are made of copper. Fig. 2 shows the mold design with the cooling channel insert system. This system controls the plate temperature, which includes pre-heating the plates to the initial temperature at the beginning of the experiment, and cooling them after the heating period by receiving the water from the mold temperature control. During each run of the experiment, the temperature will be measured at points T1, T2 and T3. Fig. 3 shows the experiment mold plate insert with the wrapped coil and cooling channel system.

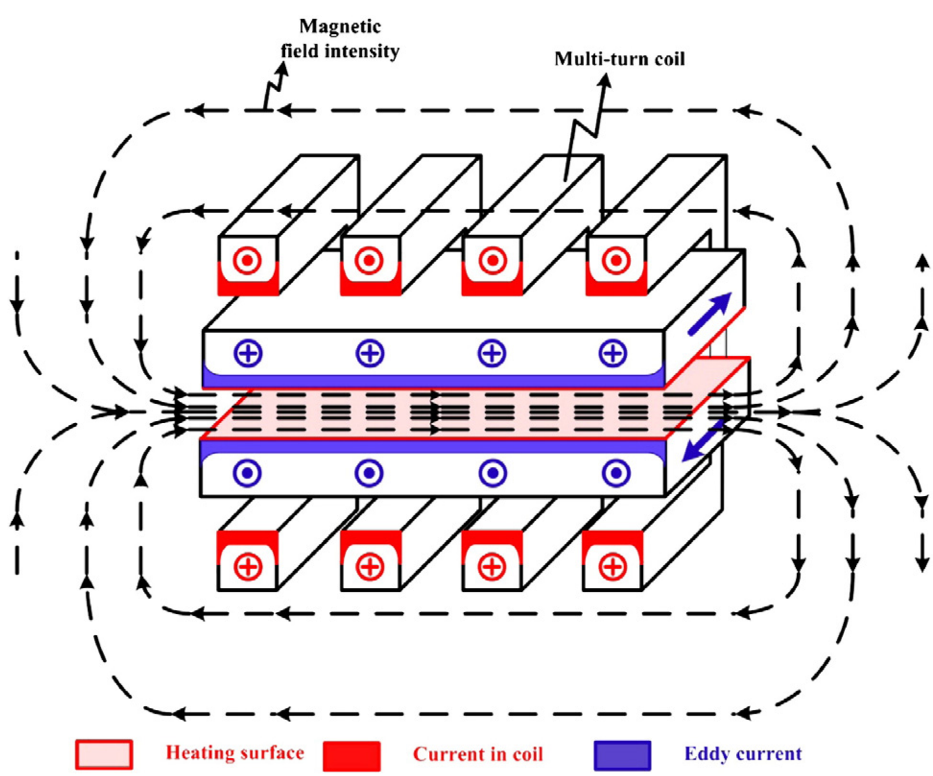

Fig. 1. Principle of externally warped coils induction heating.

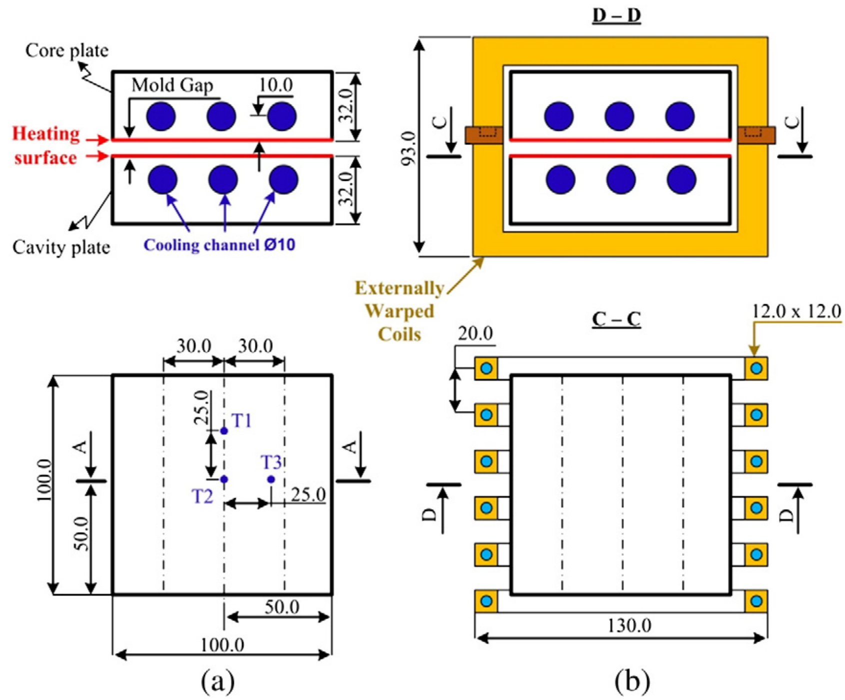

Fig. 2. The dimension of mold plate, measured position (a) and multi-turns coil position (b).

To observe the temperature at the plate surface, an infrared thermal imaging system (Avio NEO THERMO TVS-700) and thermal couples were used to measure the mold temperature. The experimental results were collected to verify the simulated predictions. Three measurements were recorded at each position, and the average values from these five measurements were used for analysis and correlation. In this study, a pair of mold plates will be pre-heated to 40 °C. The induction heating machine will then be turned on to heat the mold plates. The heating rate and temperature distribution of the mold plates will be observed as two aspects of the system are manipulated: the coil design and the mold gap. The parameters of the experiment and simulation are shown in Table 1.

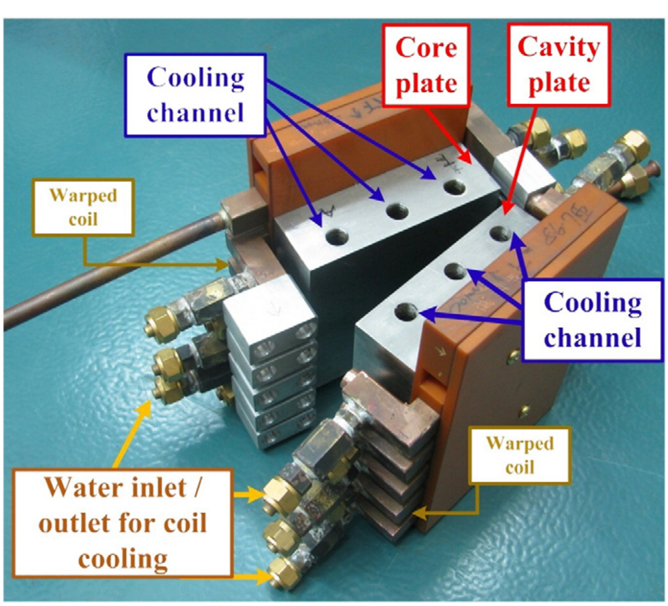

Fig. 3. Experimental mold design.

In all cases, pairs of plates made of stainless steel 420 were used to study the effect of coil design and mold gap on the heating rate. In every case, by experiment and simulation, the temperatures at points T1, T2 and T3 will be collected after 5 s, 10 s, and 15 s of heating. These results will be compared to study the differences in heating rate and temperature distribution. Using simulations, the effect of the heating period on the mold was also observed at cross-section A–A.

A 3D coupled electromagnetic-thermal and cooling analysis was performed by ANSYS software and compared with the experimental results. The detail of simulation can be found elsewhere [15]. Fig. 4 shows the simulation model and the mesh model of the serial and parallel coil. As in the experiment, a pair of mold plates was used for the simulation. The mold plates are inserted inside the coil. The material properties of the mold plate, the conductor, and the air are shown in Table 2. In simulation, the heat transfer mode around all external surfaces of mold plate was set at free convection to the air, with an ambient temperature of 25 °C and a heat transfer coefficient of 10 W/m^2 K [19].

Table 1
Experiment of externally warped coils induction heating.

Case	Coil type	Number of turns	Mold gap (mm)
A1	Serial	6	2
A2	Parallel		
B1		5	
B2		6	
B3		7	
C1	Serial	6	1
C2			2
C3			3
C4			4
C5			5
C6			6

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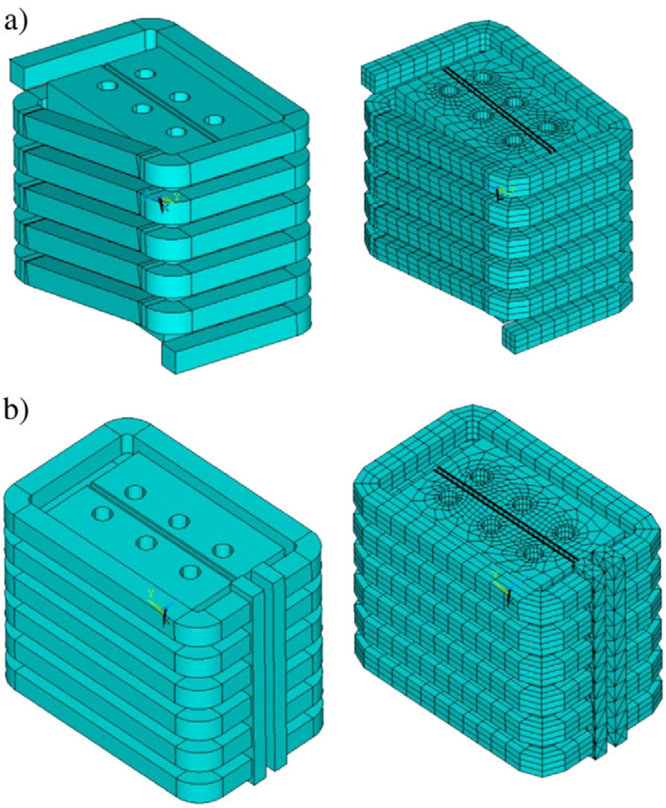

Fig. 4. Simulation model and mesh model of serial coil (a) and parallel coil (b).

4. Results and discussions

4.1. Effect of the serial and parallel coil on the heating process

To observe the effect of the serial and parallel coil on the externally wrapped coil induction heating, pairs of plates (100 mm × 100 mm × 32 mm, 420 stainless steel) combined with an externally wrapped coil induction heating system were used. The variation in the mold surface temperature (at point T2 in Fig. 2) versus time under different conductor types for a heating time of 15 s are described in Fig. 5. Based on the properties of the serial and parallel current, at the same power, the current intensity flowing in the coil of serial design is much higher than the parallel design. Therefore, the magnetic intensity as well as the eddy current of the serial design is far stronger than the parallel design.

In this case, for an initial mold temperature of 40 °C, after 15 s heating, 6 turns, and the pitch of 20 mm, the mold surface temperature at point T2 reaches 159.9 °C and 68.3 °C with serial and parallel coils, respectively. The heating rate of the serial coil thus reached 8.0 °C/s. In the field of injection molding, this speed is sufficient to raise the mold surface temperature above the glass transition

Table 2
Material properties [18].

Physical property	Density	Electrical resistivity	Relative permeability μ	Specific heat	Thermal conductivity
Unit	kg/m^3	Ω-m	–	J/kg-K	W/m-K
Air at 25 °C	1.18	–	1	1000	0.0256
Stainless steel 420 (ISO 683/134)	7700	5.50E −07	200	448	14
Copper	8940	1.71E −07	0.99	392	400

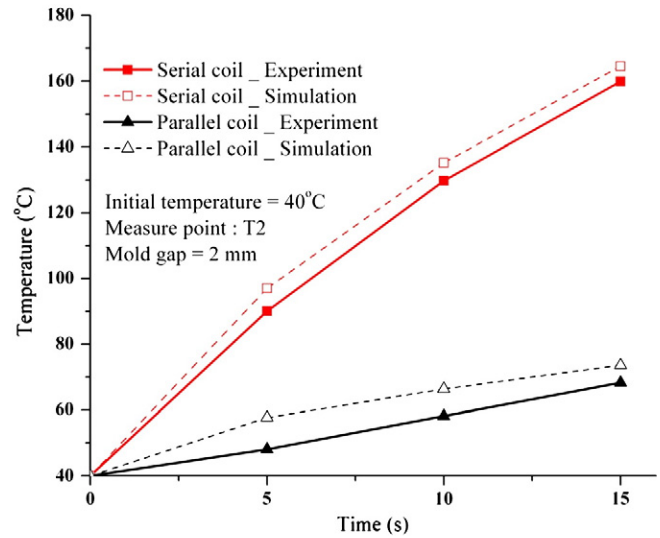

Fig. 5. Variation of surface temperature at point T2 with time at various coil designs.

temperature of most resins within a few seconds of heating. The simulation using ANSYS software with the parameters given in Table 2 shows that the history of the temperature at T2 is nearly the same as the experimental results for both types of coils.

In the field of injection molding, the temperature distribution at the core and cavity surface has a strong influence on the warpage of the product. After 10 s heating of the serial and parallel coil design, with an initial temperature of 40 °C, 6 turns, and a coil pitch of 20 mm, Fig. 6 shows a comparison of the temperature at the 3 points for the serial and parallel coil designs. This result shows that the temperature difference of the 3 points T1, T2 and T3 is approximately 20.3 °C and 4.0 °C, for the serial and parallel coils, respectively. This is because of the intensity of current in each turn of the coil. With the parallel coil, the current is almost the same in all turns, meaning that this design results in more uniform heating. For the serial coil, the magnetic flux density is stronger near the center turn, so, the heating effect will be stronger at the center turn, and the result is that the heating process is less uniform. In general, based on these results, the parallel design

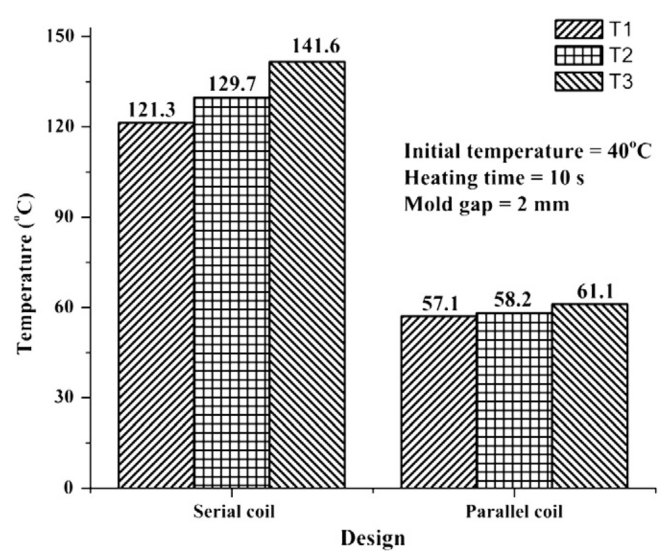

Fig. 6. Comparison of temperature at T1, T2 and T3 on the core plate at various coil design.

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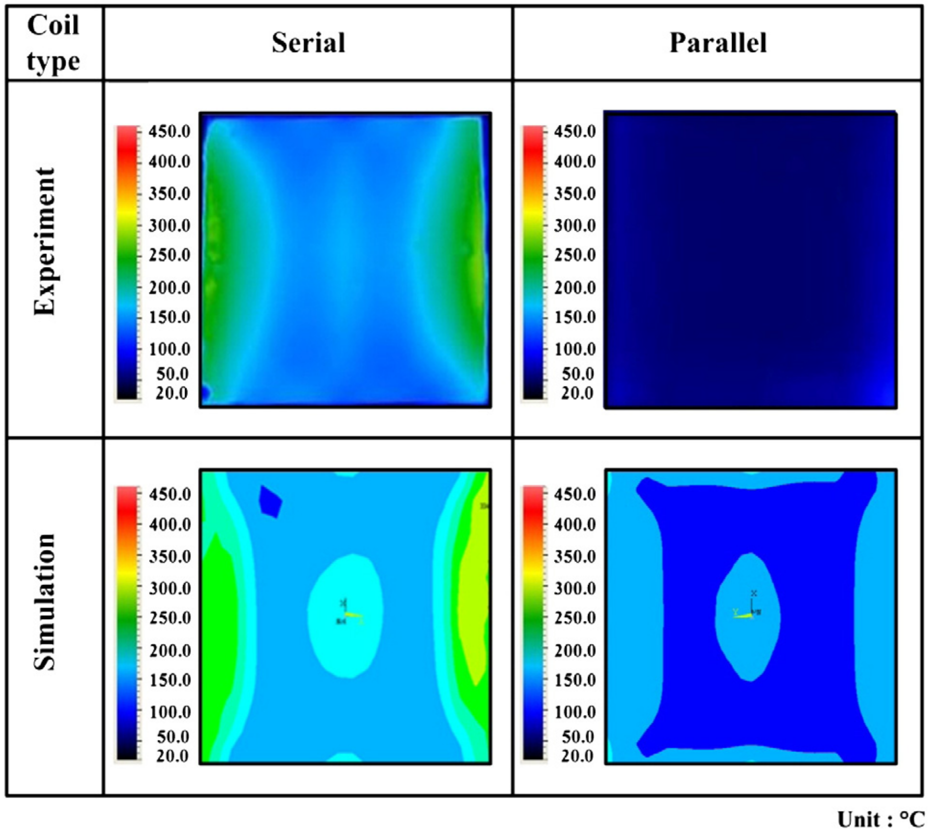

Fig. 7. Core plate surface temperature distribution with different coil types under the heating time of 10 s.

appears to be better if the goal is temperature uniformity. However, the serial design has a clear advantage in heating rate on all points.

By experiment and simulation, the temperature distribution at the heating surface was analyzed. The infrared thermal image system (Avio NEO THERMO TVS-700) was used to investigate the influence of the serial coil and parallel coil design on the heating efficiency. Fig. 7 shows that when the serial coil is used, the high temperature will be concentrated at the left and right sides of the heating surface. This is likely due to the closer distance between these areas and the induction coil, which support a stronger magnetic flux density. Therefore, at these locations, the heating effect has a stronger trend than other areas. Another result on the core surface is a slightly higher temperature at the center area. This is because of the magnetic density at the center of the wrapped coil, which is stronger than the outside [18]. Furthermore, the simulation also shows a good agreement in temperature distribution in both types of coil.

The difference in temperature at the heating surface between the core plate and cavity plate is compared in Fig. 8. Based on the experiment result, with the initial temperature of 40 °C, and after 10 s heating, the difference in temperature between the core plate and the cavity plate is less than 3 °C. This is an advantage because it helps to reduce the warpage of product after the part is ejected. Fig. 9 shows the temperature distribution of the core and cavity plate for both the experiment and the simulation. Based on this result, the temperature distribution at the heating surface between the core and cavity plate are almost the same.

4.2. Effect of the number of turns on the heating process

On the basis of the above design, because of the advantage of heating rate, the serial coil will be used for the next study. With an initial mold temperature of 40 °C and a coil pitch of 20 mm, the study will investigate inductor designs with 5, 6 and 7 turns. Fig. 10 shows the temperature history of the experiment and simulation with a heating time of 15 s. The results show that the greater the number of turns, the higher the heating rate. This is because as the number of turns increases, the strength of the magnetic intensity that can be supported near the heating surface rises, increasing the eddy current and yielding higher heating speeds at the heating surface. In the experiment, after 15 s, the

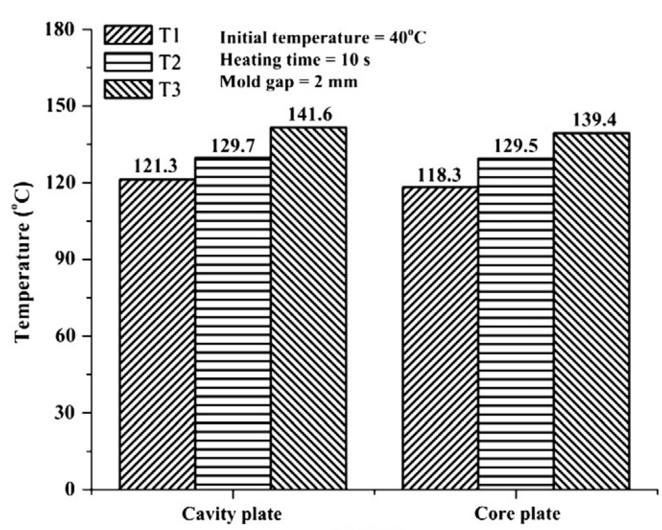

Fig. 8. Comparison of temperature at T1, T2 and T3 on the surface of core plate and cavity plate.

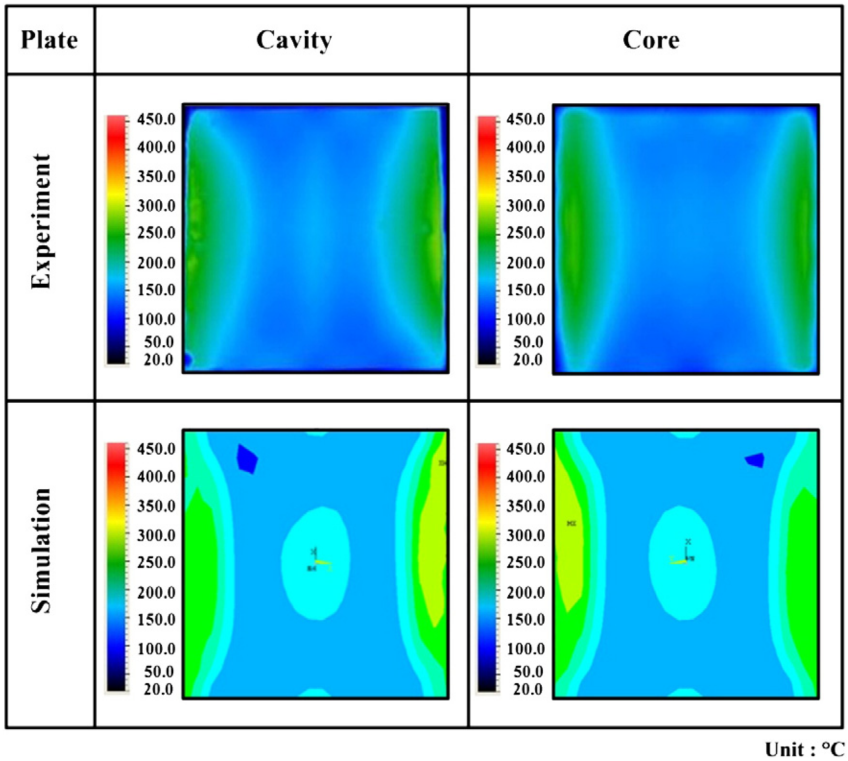

Fig. 9. Temperature distribution of core and cavity plate with the heating time of 10 s, serial coil, and mold gap of 2 mm.

temperature at point T2 reaches 113.5 °C, 159.9 °C, and 198.7 °C for 5, 6, and 7 turns, respectively. The results of the simulation show good agreement with the experimental results for all heating periods. Fig. 11 shows a comparison of temperatures at point T1, T2 and T3 after 10 s heating. Based on this result, the temperature at the three points depends strongly on the number of turns. The temperature difference between the three points in each case varies from 15 °C to 20 °C. Fig. 12 gives the temperature distributions for the simulation and the experiment. As in the above cases, the higher temperature is located at the left and right side of the heating surface, and there is an increase of temperature in the center area of the heating surface. When the number of turns is increased, the heating effect rises strongly, especially in the left and right sides and the center area of the heating surface. This difference can be observed in the simulation in Fig. 13. These results show the temperature distribution of section A–A. The detail view shows the different temperature distributions when the number of turns changes. This result also shows that as the number of turns increases, the temperature rise. Further, the concentration of temperature near the heating surface can clearly be seen in all detail views. This property of heating near the heating surface is an advance that facilitates a more rapid cooling step. The 3D isotropic view show the temperature distribution of the two mold plates with the cross-section A–A. It shows that all the outside

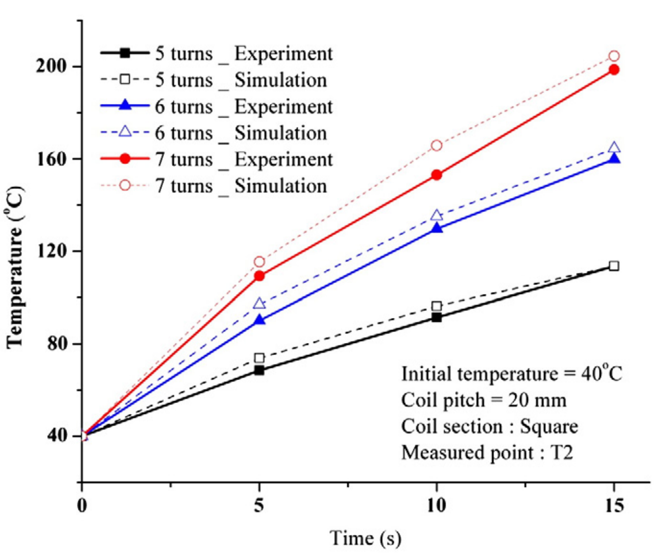

Fig. 10. Comparison of temperature at point T2 with different number of turns.

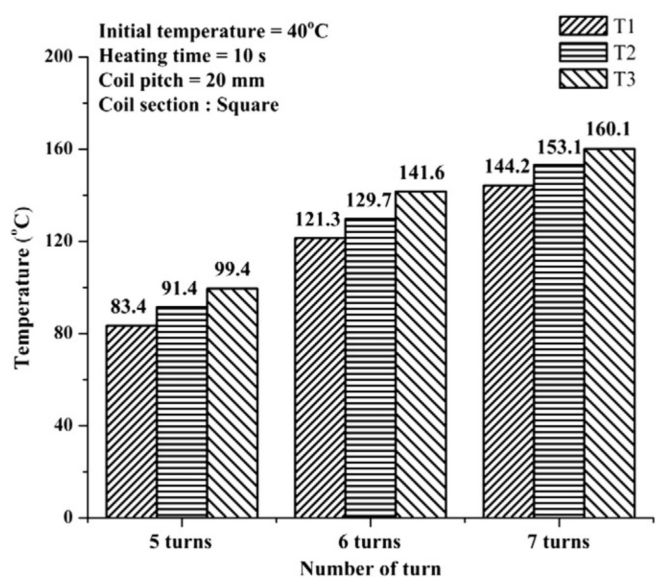

Fig. 11. Comparison of temperature at T1, T2 and T3 on the surface of core plate with different number of turn.

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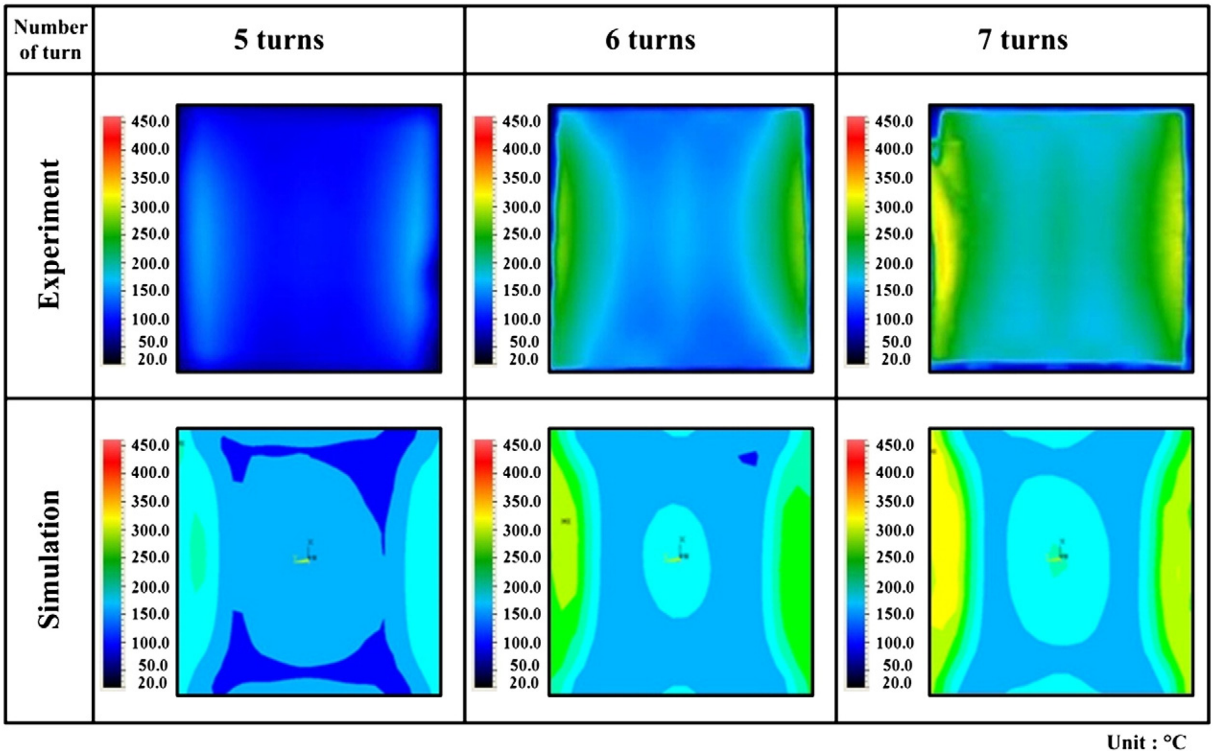

Fig. 12. Temperature distribution of core plate with the heating time of 10 s, coil pitch of 20 mm, and square section of coil.

faces of the plates are also heated, and that the greater the number of turns, the greater the heating influence. However, almost all the heating effect occurs along the inside surface of both plates.

4.3. Effect of mold gap on the heating process

To investigate the effect of mold gap on the heating efficiency, the mold gap was varied from 1 mm to 6 mm, with serial coil induction heating, under simulation. After the heating time of 15 s, with an initial temperature of both mold plates of 40 °C, Fig. 14 shows that the temperature at point T2 is 166.7 °C, 164.5 °C, 155.4 °C, 131.6 °C, 119.7 °C and 106.1 °C with mold gap of 1 mm, 2 mm, 3 mm, 4 mm, 5 mm and 6 mm, respectively.

In injection molding, the gap between the two mold plates will determine the thickness of the plastic product. In general, the thickness of part is usually in the range of 1 mm to 3 mm. Therefore, it is common to vary the gap between the core plate and cavity plate real molds from 1 mm to 3 mm. In this paper, mold gap of 1 mm, 2 mm and 3 mm were chosen for the experiment. Temperatures at point T2 was collected and compared with the simulation results.

Fig. 15 shows the temperature at point T2 after 15 s heating with the serial coil, from an initial temperature of 40 °C. The result also shows that with larger mold gap, the temperature at T2 also has a negative heating effect. When the mold gap changes from 1 mm to 3 mm, the temperature at point T2 falls from 166.5 °C to 152.0 °C in experiment and 166.7 °C to 155.4 °C in the simulation. However, for the range of 1 mm to 3 mm, this decrease in temperature is not unacceptable. Therefore, in real applications of injection molding, externally wrapped coil induction heating will not be greatly affected.

5. Conclusions

In this study, the mold temperature control was carried out using an externally wrapped coil induction heating system combined with water cooling to achieve rapid mold temperature control for injection molding. The effect of heating on the uniformity of mold temperature for simple plate molding was evaluated. Using both experiment and simulation, the temperature at the heating surface was investigated. Based on the results, the following conclusions were obtained.

- When the coil design changes from parallel to serial, the heating rate increases from 1.8 °C/s to 8.0 °C/s. For an initial mold temperature of 40 °C and heating time of 15 s, the mold surface temperature can reach 159.9 °C and 68.3 °C with serial and parallel coils, respectively.
- The heating efficiency of the coil designs varies significantly. However, in both experiments and simulation, the temperature distribution is almost the same for either coil design. A higher temperature appears at the left and right side of the heating surface. At the center of the heating surface, the temperature is slightly higher than the surrounding area.
- For the three points measured on the heating surface in the experiment, the temperature difference is generally lower than 22 °C. The parallel coil shows a better uniformity than the serial coil. However, on the heating surface, in both the serial and parallel coil designs, the temperature difference between the core plate and the cavity plate is almost the same, and is less than 3 °C.
- As the number of turns changes, the heating rate varies significantly. The maximum heating rate is 10.5 °C/s at point T2 with 7 turns. With an initial mold temperature of 40 °C, a square coil, and a heating time of 15 s, the temperature at point T2 is 113.5 °C, 159.9 °C, and 198.7 °C with 5, 6, and 7 turns, respectively.
- Although the heating effect appears on all faces of the mold plate, the main heating effect is concentrated on the heating surface of both mold plates. By simulation, this effect was observed by cross-section A–A and detail view.
- When the mold gap increases from 1 mm to 6 mm, the heating rate falls. However, when the mold gap changes from 1 mm to 3 mm, the difference in temperature caused by the heating effect is not significant. The simulation and experimental results are in good agreement.

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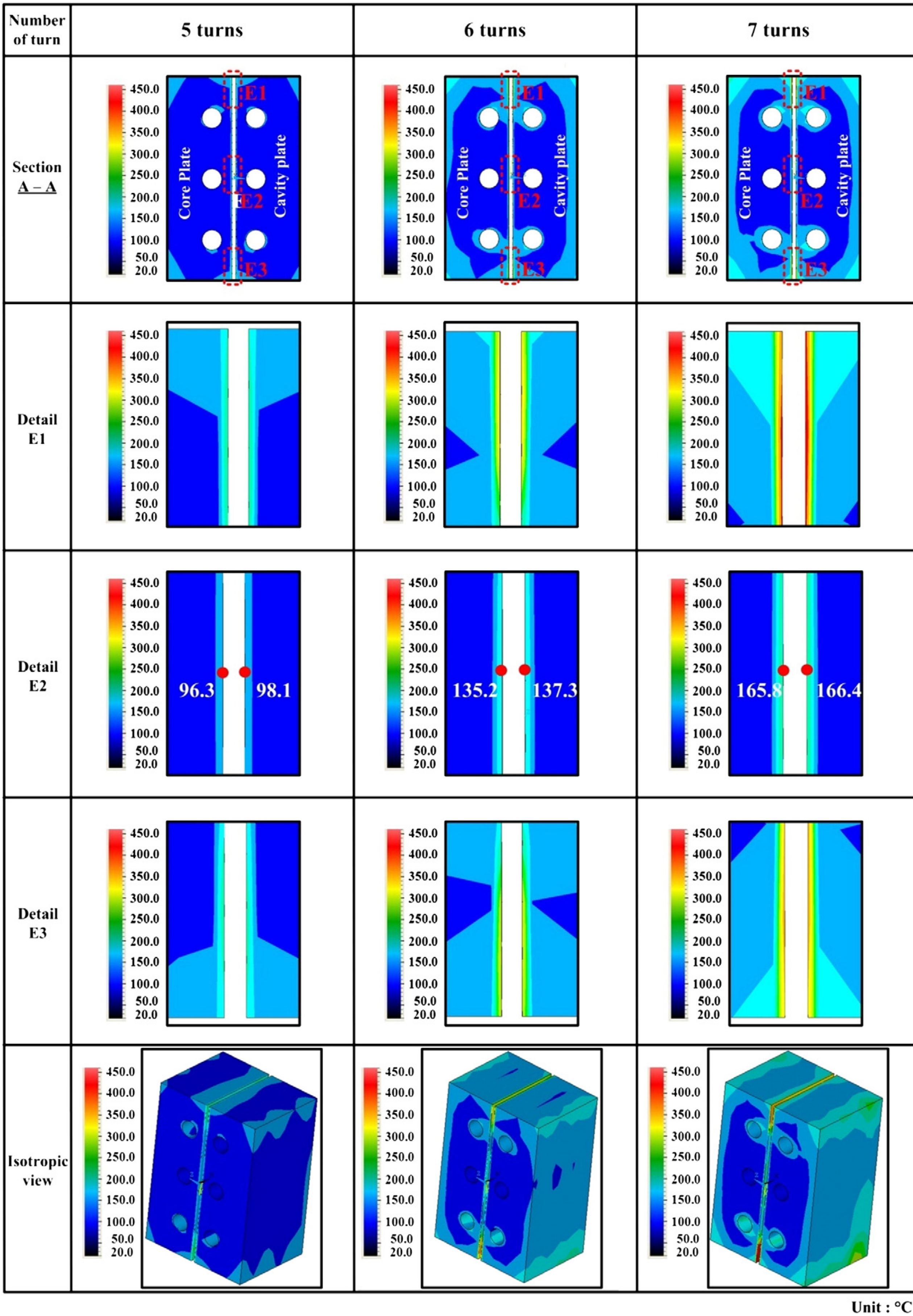

Fig. 13. Temperature distribution at section A–A with the heating time of 10 s, coil pitch of 20 mm, and square section of coil.

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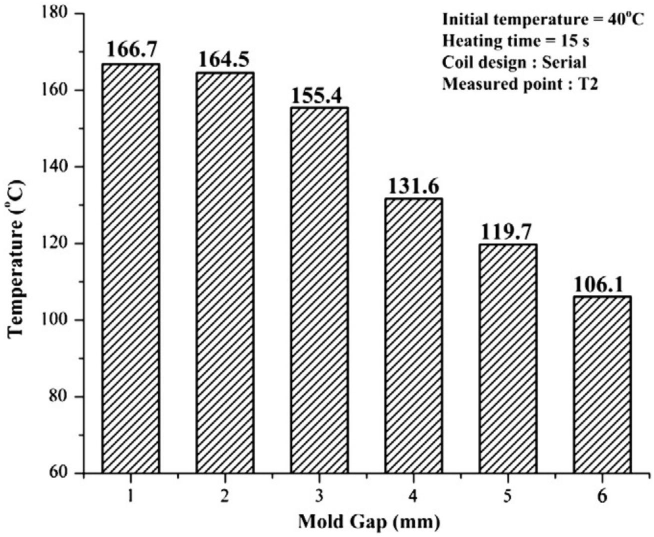

Fig. 14. Comparison of temperature at T2 on the core plate with different mold gap.

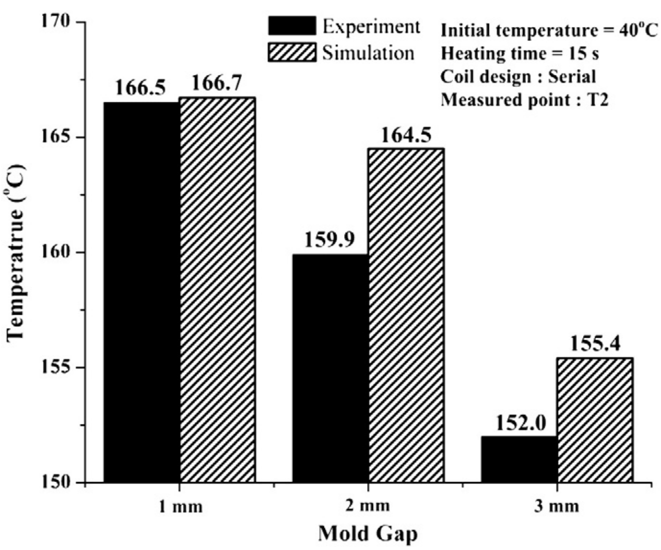

Fig. 15. Comparison of temperature at T2 on the core plate between simulation and experimental with different mold gap.

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